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JEL Codes: Q11, Q56, O13

Keywords: Rational food waste, behavioural bias, price policies.



Food Waste: You Can't Always Want What You Get

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Abstract

Food waste constitutes a significant economic inefficiency and should therefore be a central policy issue. While in low-income countries food waste is often associated with poor harvesting, storage and transportation conditions, in middle- and high-income countries consumers' behavior is considered to be the main driver of this problem. The general aim of our paper is to contribute to the understanding of food waste. We focus on household food waste and the economic mechanisms behind it. We propose a stylized model in which food waste appears as an economic decision of households. Our framework of “rational food waste” relies primarily on consumer behavioural biases, which could be further encouraged by aggressive pricing strategies such as quantity discounts.

Keywords: Rational food waste, behavioural bias, price policies

Journal of Economic Literature: Q11, Q56, O13

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1 Introduction

Food waste constitutes a significant economic inefficiency and should be therefore a central policy issue (for instance, Hamilton and Richards, 2019). Bellemare et al. (2017) point out that, according to the Food and Agriculture Organization of the United Nations (FAO), a quarter to a third of all food produced in the world is wasted. In particular, the Food Waste Index Report (UNEP, 2021) estimates that around 931 million tons of food were wasted in 2019. For the US, Yu and Jaenicke (2020) observe that 30-40% of the total food supply goes uneaten, resulting in losses of more than \$160 billion. Similarly, Bellemare et al. (2017) notice that estimates of food waste in the US range from 35 million tons (US Environmental Protection Agency, 2016) to 103 million tons (FAO, 2011a). In this regard, as mentioned by Smith and Landry (2020), in 2015 the US joined the UN goal to cut the amount of unconsumed edible food in half by 2030 (UN, 2015).

While in low-income countries food waste is often associated with poor harvesting, storage and transportation conditions, in middle- and high-income countries consumers' behavior is considered to be the main driver of this problem (Blakeney, 2019; Ellison, 2020; and Lusk and Ellison, 2020). According to the FAO (2011b), estimates of per capita food waste by consumers in Europe and in the US range between 95-115 kg/year, which contrast with 6-11 kg/year in sub-Saharan Africa and South/Southeast Asia. Moreover, the food wasted by households in high-income countries represents about the entire food production of sub-Saharan Africa (UN, 2012). The UNEP (2021) observes that households accounted for 61% of total food waste in 2019, which represents 11% of the world total production. In the US, households are responsible for almost half of all discarded food (Heller, 2019). Yu and Jaenicke (2020) estimate that the average household in the US wastes 31.9% of the food it buys, implying an annual consumer-level food waste of about \$240 billion. For the EU, Jensen et al. (2016) found that food retail, households and food service account for about 70% of the total food amount that exits the supply chain, while food production and processing were behind the remaining 30%. Households happen to be the biggest contributors, representing

53% (47 million tons) of EU food waste. In a recent report for the UK, over 70% of the food wasted in 2022 (post-farm gate), equivalent to a value of over £14 billion a year, comes from households (WRAP, 2023).

In addition to the economic inefficiency implied by discarding food, Blakeney (2019) also underlines the impact of food waste on food security. It is estimated that 815 million people have insufficient food to meet their nutrient needs, and 45% of all deaths in children under five are due to malnutrition (FAO, 2014). Moreover, global food demand is expected to increase by at least 60% in 2050 compared to 2006, while climate change will reduce arable land available for food production (FAO, 2016). Indeed, many studies also point out the environmental impact of food waste, both directly in relation to the discarding of unwanted food and indirectly in relation to the energy inputs used (among others, FAO, 2013; Blakeney, 2019; or Yu and Jaenicke, 2020).

The general aim of our paper is to contribute to the understanding of food waste. We focus on household food waste and the economic mechanisms behind it. More precisely, we propose a stylized model in which food waste appears as an economic decision of households. Our framework of “rational food waste” relies primarily on consumer behavioural biases, which could be further encouraged by aggressive pricing strategies such as quantity discounts.

The model describes how a representative household prepares a meal using different types of ingredients. Although households can grow part of their food, they can also purchase and store some of the ingredients. Meals are then made by combining three categories of ingredients: home-grown ingredients and purchased fresh and processed foods. Considering the production of home-grown ingredients, as well as storage and meal preparation technologies, households get utility from the corresponding composite meal. However, we also assume that a household’s preferences may depend on the processed foods consumed. In our stylized framework, this specific taste for processed foods encapsulates the sales and marketing practices of the processed and ultra-processed food industry to attract consumers. These strategies range from including additives in (ultra-)processed foods in order to increase their

palatability and appeal to aggressive marketing techniques (see, for instance, Moodie et al., 2013; Hall et al., 2019; and Perona, 2022). We show that this taste can create a mismatch between households' preferences and the nutritional contribution of processed foods, leading to food waste. Moreover, if this bias is systematically nurtured, food waste would be persistent over time. We also study the role played by non-linear food prices in this regard. We find that quantity discounts can sustain even higher levels of food waste.

Models of food waste as rational decisions of households are generally divided into two main strands. On the one hand, Katare et al. (2017), Hamilton and Richards (2019) and Yu and Jaenicke (2020) follow the idea that households use inputs (e.g., ingredients purchased at a grocery store) at a certain price to produce consumable food that provides them utility. Katare et al. (2017) directly assume that part of the consumable food is wasted, which depends on factors such as human capital, education or conservation technology. Hamilton and Richards (2019) consider that it requires effort from the household to use those inputs. Building on this idea, Yu and Jaenicke (2020) show that sell-by dates can actually induce food waste. Here the effort is represented by a "cost" of reducing food waste. On the other hand, several papers follow the theory of time allocation by Becker (1965). A time constraint is explicitly considered in Morris and Holthausen (1994), Höjgård, Jansson and Rabinowicz (2013), and Lusk and Ellison (2017), where food preparation takes time and therefore reduces the available time for work and leisure.

These models underline different economic mechanisms that can explain household rational food waste. However, most of them have a limited normative scope because lowering rationally chosen levels of food waste would reduce households' welfare. Morris and Holthausen (1994) and Katare et al. (2017) are exceptions in this regard, where consumers may not fully integrate the social cost (externalities) of the food discarded. Moving away from the standard approach of household food waste, Lusk and Ellison (2020) suggest exploring the role played by information asymmetries or behavioural biases. Our model is related to this alternative, where a preference for processed food can bias household choices

against the nutritional contribution of these inputs. The importance of this type of bias is well known in the literature, such as in problems of self-control or time-inconsistent preferences (see Frederick et al., 2002). In particular, visceral factors are often manipulated by salespersons, realtors and firms (Loewenstein, 1996; or Laibson, 2001). Moreover, the influence of food industry strategies, such as palatability modification, the use of large portion sizes and aggressive marketing strategies, and the increasing consumption of ultra-processed foods have been largely documented in the medical literature (for instance, Monteiro et al., 2010; Juul and Hemmingsson, 2015; Rauber et al., 2018; Latasa et al., 2018; Blanco-Rojo et al., 2019; and Monteiro et al., 2019).

The remainder of the paper is organized as follows: Section 2 introduces our model by specifying how households prepare their meals. We then set the intertemporal problem of the representative household. In Section 3 we characterize the solution to this problem. Section 4 studies the dynamics, paying attention to the possibility of persistent food waste. In Section 5 we consider the case of non-linear food pricing, focusing on quantity discounts as an aggressive pricing policy. Section 6 concludes.

2 A model of food waste

2.1 From the shop to the plate

To understand how households can rationally waste food, we develop a model that describes how a meal is prepared from different types of ingredients, starting with purchasing some of those ingredients and storing them. Households may also grow part of their food, such as fruits, vegetables, milk, cereals, poultry, meat or eggs. Meals will be prepared using these three categories of ingredients: purchased fresh and processed foods as well as home-grown ingredients. Let us define and describe in detail all the processes involved in the storage, transformation and consumption of food.

We assume that households consume a quantity c_t of a single composite meal in each

time period t . This meal is produced with home-grown ingredients, u_t , as well as fresh and stored food, v_t and z_t . At every period t the household purchases a quantity b_t of goods. This basket is made up of a quantity v_t of fresh foods, which must be consumed on the same date t , and a quantity $b_t - v_t$ of processed foods that can be stored. In our stylized model, “processed foods” correspond to either processed or ultra-processed foods in the NOVA classification system.¹ Here, we consider ultra-processed foods because, as highlighted in the literature, they contain ingredients specifically added to extend their shelf life (e.g., Gibney, 2019; Blanco-Rojo et al., 2019; Monteiro et al., 2019; Adams et al., 2020). The unit price of a basket b_t is $p(b_t)$. More specifically, we consider that the cost of a basket b_t is $p(b_t)b_t = \tilde{p}b_t^\theta \geq 0$, with $0 < \theta \leq 1$ and \tilde{p} a positive constant. $\theta = 1$ represents the usual case of linear prices, while $0 < \theta < 1$ stands for the pricing strategy of quantity discounts. We study in Section 5 persistent food waste under linear prices while Section 6 studies the effect of quantity discounts, where the unit price $p(b_t) = \tilde{p}b_t^{\theta-1}$ is a decreasing convex function of b_t . Note that it would be straightforward in our framework to include specifications for the prices of fresh and processed foods, focusing the aggressive pricing policies on the latter.

Assuming for simplicity that processed foods can be stored only for one period, the stock of food available for the next period is

$$s_{t+1} = \varphi(b_t - v_t), \tag{1}$$

where $\varphi(\cdot) : \mathbb{R}^+ \rightarrow \mathbb{R}^+$ represents the storage technology, and it may depend on the quantity stored. φ is a positive function with $\varphi' < 1$. Hence, some of the stored food will spoil from

¹Foods are often classified in 4 groups following NOVA (Monteiro et al., 2019): unprocessed or minimally processed food (G1), processed culinary ingredients (G2), processed foods (G3), and ultra-processed foods (G4). G2 are substances rarely consumed by themselves, used to prepare, season and cook G1 foods. These are obtained directly from G1 or from nature by industrial processes such as pressing, refining, grinding, milling, and drying. G3 refers to products made by adding salt, oil, sugar, or other G2 ingredients, to G1 foods, using preservation methods such as canning, bottling and/or non-alcoholic fermentation. The aim of these processes is to increase the durability and sensory characteristics of G1 foods. G4 products are combinations of ingredients, many of which are exclusive to industrial use, resulting from industrial processes often requiring sophisticated equipment and technology. The main goal is to obtain hyper-palatable, highly profitable, ready-to-eat foods.

one period to the next to capture the possibility of storage inefficiencies: if $v_t < b_t$, a quantity $b_t - v_t - \varphi(b_t - v_t)$ of the stored food will be lost before the food can be used in the next period. This is what we will later define as “mechanical waste” because it is not related to any decision of the household.

As stated above, households consume a single composite meal, obtained from home-grown ingredients and a mixture of fresh and stored purchased foods. For the sake of presentation, we organize the preparation of the meal in two distinct stages: (i) preparing purchased foods and then (ii) assembling them with home-grown ingredients. In the first stage, the fresh and stored foods are combined to become m_t , a purchased base for the final meal. This base is obtained using a transformation technology h :

$$m_t = h(v_t, z_t), \tag{2}$$

where v_t is fresh food and z_t is the amount of processed food taken from the pantry, so that we have necessarily $z_t \leq s_t$. Neither fresh nor processed foods will be essential in the preparation of m_t , so households may decide at any time not to buy fresh or processed foods. Furthermore, we assume that they are not perfect substitutes. The medical literature widely supports their very different nutritional contributions. For example, Steele et al. (2017), Rauber et al. (2018) and Konieczna et al. (2022) highlight the poor quality and unbalanced diet behind the consumption of ultra-processed foods as well as their link to metabolic syndrome as they displace healthier unprocessed or minimally processed foods. In particular, Srour et al. (2019) find a strong association between the consumption of ultra-processed foods and a higher risk of cardiovascular, coronary and cerebrovascular diseases, while Blanco-Rojo et al. (2019) identify a higher mortality risk.

The medical literature also points out that excessive consumption of ultra-processed foods significantly disrupts whole-body metabolism (see, for instance, Monteiro and Cannon, 2012; Moodie et al., 2013; and Lesser et al., 2015). Specifically, evidence shows a clear dose-

response relationship, in which organs such as the liver or muscles cannot cope with levels of fat and sugar beyond a certain threshold, thus becoming dysfunctional (among others, Wasserman, 2009; Rippe et al., 2016; Henney et al., 2023; Lee et al., 2023). Therefore, in line with these studies, we will assume that the transformation technology (2) is increasing in v and z . However, it decreases in z beyond a certain threshold of processed food intake.²

In addition to purchased ingredients, we assume that the household has some self-production capacity, such as land or livestock, which yields a harvest k_t . Part of the harvest is used for consumption, u_t , while the rest is used to purchase b_t and continue household production in the next period. The composite meal c_t is obtained with a final assembly technology g , using u_t and m_t :

$$c_t \leq g(u_t, m_t). \quad (3)$$

In this model we can identify two sources of food waste. As observed above, the first one is purely mechanical due to storage inefficiencies. We denote by w_t^m the mechanical waste at period t , and it is defined as

$$w_t^m \equiv b_t - v_t - \varphi(b_t - v_t) \geq 0. \quad (4)$$

The second source is intentional, meaning that the household may rationally decide to buy more than what it actually consumes. We denote intentional waste at time t by w_t^i , which is defined as

$$w_t^i \equiv s_t - z_t \geq 0. \quad (5)$$

Being aware of the food price function, home-grown ingredients and storage technology as well as meal preparation functions, the household chooses the amount of fresh and processed food to buy. The household also decides the quantities of processed food to consume out of the pantry, the size of its future stock of stored food, and the part of their harvest to be

²Threshold levels can be endogenised by including health as an additional household decision variable, as in Grossman (2000) or Goulão and Perez-Barahona (2014), for example. This would add an additional layer of complexity without affecting the overall conclusions.

either consumed or used to generate home-grown production for the following periods.

2.2 The household problem

The objective of our representative household is to maximize overall welfare measured as follows:

$$\max_{\{c_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t U(c_t, s_{t+1}), \quad (6)$$

where β is the standard agent's time discount, verifying that $0 < \beta < 1$. Function U is the instantaneous utility function. We assume that households derive utility from the consumption of the composite meal c_t prepared from fresh, processed, and home-grown ingredients. Additionally, they may also have preferences regarding processed foods, s_{t+1} . As observed in the introduction, a specific taste for processed ingredients summarizes the result of different industrial strategies aimed at creating hyper-palatable and appetizing (ultra-) processed foods.

Household's decisions are subject to a number of constraints. First, there is a resource constraint. To provide the simplest possible framework, we consider that households can produce part of their food using capital k_t , which can be interpreted as the stock of seeds or livestock at time t . The home-grown production technology is f and, therefore, the household's income at time t is $f(k_t)$, i.e., today's crops. This can be used to produce in the next period, k_{t+1} , used to buy food, $p(b_t)b_t$, or added directly to today's composite meal, u_t . Hence,

$$f(k_t) \geq k_{t+1} + p(b_t)b_t + u_t. \quad (7)$$

Additionally, as described above, the representative household takes into account the storage technology (1). It also considers the preparation of the composite meal, which is described by the preparation of purchased ingredients (2) and the final assembly (3).

The problem of the representative household can be then formalized as follows: Taken

$p(b_t)$ as given,

$$\max_{\{c_t, s_{t+1}, u_t, b_t, v_t, z_t\}_{t=0}^{\infty}} \sum_{t=0}^{\infty} \beta^t U(c_t, s_{t+1}), \quad (\mathcal{P})$$

which at every time t is subject to the constraints

$$\left\{ \begin{array}{l} u_t + p(b_t)b_t + k_{t+1} \leq f(k_t), \\ s_{t+1} = \varphi(b_t - v_t), \\ m_t = h(v_t, z_t), \\ c_t \leq g(u_t, m_t), \quad z_t \leq s_t, \quad \text{and} \quad v_t \leq b_t. \end{array} \right.$$

All variables are positive, i.e., $c_t \geq 0, u_t \geq 0, v_t \geq 0, z_t \geq 0, b_t \geq 0, s_{t+1} \geq 0, k_{t+1} \geq 0$, and the initial values of capital stock and stored food, $(k_0, s_0) \in \mathbb{R}_+^2$, are given.

We maintain the following set of standard assumptions throughout the paper:

Assumption 1. $U : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$ is continuous, strictly increasing and concave in (c, s) . U is twice continuously differentiable on \mathbb{R}_{++}^2 and its partial derivatives satisfy the following Inada conditions: $\lim_{c \rightarrow 0} U_c(c, s) = +\infty$, $\lim_{c \rightarrow \infty} U_c(c, s) = 0$, $\lim_{s \rightarrow 0} U_s(c, s) = +\infty$ and $\lim_{s \rightarrow \infty} U_s(c, s) = 0$, $\forall c, s > 0$.

The positiveness of the composite meal and processed foods for all $t \geq 0$ follow from the Inada conditions. Hence, at the optimum, we will have that $c_t > 0$ and $s_t > 0$ for every t . In particular, under Assumption 1, there will always be mechanical waste. Indeed, since s_t must be positive at all t , there will be a fraction of the stored food that will spoil in each period due to the technological inefficiencies of storage.

The home-grown production f is neoclassical and the storage technology an increasing function:

Assumption 2. $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ is twice continuously differentiable, strictly increasing, strictly concave and satisfies $f(0) = 0$, $\lim_{k \rightarrow 0} f'(k) = +\infty$, $\lim_{k \rightarrow \infty} f'(k) = 0$.

Assumption 3. $\varphi : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ is continuously differentiable, strictly increasing and satisfies $\varphi(0) = 0$.

Fresh and processed foods are combined using the transformation technology h , which satisfies:

Assumption 4. $h : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$ is continuously differentiable on \mathbb{R}_{++}^2 and satisfies $h(0, 0) = 0$, $h(0, z) > 0$ for $z > 0$, $h(v, 0) > 0$ for $v > 0$, $h_v(v, z) > 0$ and $h_{zz}(v, z) \leq 0$.

As observed above, we assume that none of the ingredients purchased are essential. Furthermore, the concavity relating to processed foods comes from the medical literature, underlying the role played by metabolic thresholds.

Finally, we also need some assumptions on the assembly technology g :

Assumption 5. $g : \mathbb{R}_+^2 \rightarrow \mathbb{R}_+$ is continuously differentiable on \mathbb{R}_{++}^2 and satisfies $g(0, 0) = 0$, $g_u(u, m) > 0$ and $g_m(u, m) > 0$.

Since U and g are strictly increasing in their arguments, constraints (3) and (7) will be binding at the household's optimum. The household will consume the entire composite meal, i.e., $c_t = g(u_t, m_t)$, which implies that cooked meals will never be wasted in our model. Note that food waste resulting from this channel has been often studied in previous literature. Therefore, the total food waste in our economy, w_t , is the sum of mechanical and intentional food waste: $w_t \equiv w_t^m + w_t^i$.

3 Household choices

Under our set of assumptions, the classical approach (e.g., Le Van and Morhaim, 2002; and Le Van and Dana, 2003) works well for proving the existence of solution for the problem of the representative household (\mathcal{P}). Let $\zeta(b) \equiv p(b)b$ the cost of basket b . Define the return function $V : \mathbb{R}_+^3 \rightarrow \mathbb{R}_+$ by

$$V(k_t, k_{t+1}, s_t) \equiv \max_{\{b, v, z\}} U(g[u_t, h(v_t, z_t)], \varphi(b_t - v_t))$$

subject to

$$\begin{cases} 0 \leq u_t + p(b_t)b_t + k_{t+1} \leq f(k_t), \\ 0 \leq z_t \leq s_t, \\ 0 \leq v_t \leq b_t. \end{cases}$$

Let $u_t^* \equiv u^*(k_t, k_{t+1}, s_t)$, $b_t^* \equiv b^*(k_t, k_{t+1}, s_t)$, $v_t^* \equiv v^*(k_t, k_{t+1}, s_t)$, and $z_t^* \equiv z^*(k_t, k_{t+1}, s_t)$ denote the solution to this optimization problem. Then, $s_{t+1} = \varphi [b^*(k_t, k_{t+1}, s_t) - v^*(k_t, k_{t+1}, s_t)]$. Define also the correspondence Γ by $\forall (k_t, s_t) \in \mathbb{R}_+^2$, $\Gamma(k_t, s_t) \equiv \{(k_{t+1}, s_{t+1}) : \exists u \geq 0, \exists b \geq 0, \exists v \geq 0, 0 \leq u + p(b)b + k_{t+1} \leq f(k_t), 0 \leq v \leq b, s_{t+1} = \varphi [b^*(k_t, k_{t+1}, s_t) - v^*(k_t, k_{t+1}, s_t)]\}$. Therefore, the problem (\mathcal{P}) of the representative household is equivalent to

$$\max_{\{s_t, k_{t+1}\}} \sum_{t=0}^{\infty} \beta^t V(k_t, k_{t+1}, s_t)$$

subject to

$$(k_{t+1}, s_{t+1}) \in \Gamma(k_t, s_t), \forall t \geq 0$$

$$k_0 \geq 0, s_0 \geq 0 \text{ are given.}$$

Since $f'(\infty) = 0$ implies the existence of a maximum sustainable level of k_t , the set of feasible sequences is included in a compact set for the product topology. The optimization problem (\mathcal{P}) then turns out to be equivalent to the maximization of a continuous function over a compact set. Hence, an optimal path exists. More precisely, we have the following proposition:³

Proposition 1. *For any $(k_0, s_0) \in \mathbb{R}_+^2$, there exists an optimal path $(\mathbf{k}, \mathbf{s}, \mathbf{c}, \mathbf{u}, \mathbf{m}, \mathbf{b}, \mathbf{v}, \mathbf{z})$*

³Bold letters in the proposition denote the time trajectory of a variable. For instance, \mathbf{x} stands for $\{x_t\}_{t \geq 0}$.

which satisfies that for every t

$$0 \leq k_t \leq \mathcal{M} \equiv \max\{k_0, \bar{k}\}, \quad 0 \leq u_t \leq f(\mathcal{M}), \quad 0 \leq p(b_t)b_t \leq f(\mathcal{M}),$$

where $\bar{k} = f(\bar{k})$. The associated optimal path of the stock of processed food \mathbf{s} and consumption of composite meal \mathbf{c} are, respectively, given by:

$$s_{t+1} = \varphi(b_t - v_t), \quad (8)$$

$$c_t = g(u_t, m_t), \quad (9)$$

where

$$u_t = f(k_t) - k_{t+1} - p(b_t)b_t, \quad (10)$$

$$m_t = h(v_t, z_t), \forall t \geq 0. \quad (11)$$

Moreover, if $k_0 > 0$ then an optimal path from (k_0, s_0) satisfies $c_t > 0, k_{t+1} > 0, s_{t+1} > 0, u_t > 0, m_t > 0$, and $b_t > v_t$ for all t .

Proposition 1 proves that there exists solution for (\mathcal{P}) according to which the stock of capital, fresh foods and the cost of the household's basket are bounded, and it satisfies the constraints of the problem. The following proposition characterizes the solution where intentional food waste may be possible:

Proposition 2. *At every t , an optimal path $(\mathbf{k}, \mathbf{s}, \mathbf{c}, \mathbf{u}, \mathbf{m}, \mathbf{b}, \mathbf{v}, \mathbf{z})$ with intentional food waste satisfies the following set of conditions. First, the Euler equation linking present and future consumption:*

$$U'_c(c_t, s_{t+1})g'_u(u_t, m_t) = \beta U'_c(c_{t+1}, s_{t+2})g'_u(u_{t+1}, m_{t+1})f'(k_{t+1}). \quad (12)$$

A second condition that relates the marginal utility from the consumption of composite meal

and the marginal utility from processed food stored:

$$U'_c(c_t, s_{t+1})g'_m(u_t, m_t)h'_v(v_t, z_t) = U'_s(c_t, s_{t+1})\varphi'(b_t - v_t). \quad (13)$$

There is also a condition of optimality associated with the quantity of fresh food purchased:

$$U'_c(c_t, s_{t+1})g'_u(u_t, m_t) [p'(b_t)b_t + p(b_t)] = U'_s(c_t, s_{t+1})\varphi'(b_t - v_t). \quad (14)$$

Intentional waste is possible along the optimal trajectory if and only if

$$g'_m(u_t, m_t)h'_z(v_t, z_t) = 0, \quad (15)$$

or, in other words, if and only if there exists a quantity of processed foods z that maximizes $h(v, z)$, i.e., its nutrient contribution. Finally, the usual transversality conditions $\lim_{t \rightarrow \infty} \beta^t U'_c(c_t, s_{t+1})g'_u(u_t, m_t)k_{t+1} = 0$ and $\lim_{t \rightarrow \infty} \beta^t U'_s(c_t, s_{t+1})s_{t+1} = 0$ ensure that the present value of the stock of capital and stored food at the end of the economy will be zero.

Proof. See Appendix A □

Furthermore, our model already underlines the role played by consumer behavioral biases. Without a taste for processed foods, these ingredients are considered only as inputs intended to prepare the final meal. And, therefore, there would not be an excessive purchase of this type of ingredient, which would have caused intentional food waste:

Corollary 1. *If households do not show a taste bias for processed foods (i.e., $U'_s = 0$), there would be no intentional food waste.*

Proof. See Appendix B □

Notice that, under our assumptions, (14) in Proposition 2 requires $p'(b_t)b_t + p(b_t) > 0$. This condition holds if and only if $-\frac{d \ln p(b)}{db} < \frac{1}{b}$, which states that the quantity discount per unit (i.e., the semi-elasticity of prices to quantity discount) cannot be too large:

Assumption 6. Consider $p(b)$ the unit price of a basket b . The semi-elasticity of prices to quantity discount is lower than $1/b$.

Assumption 6 is trivially verified in the case that there are no quantity discounts (i.e., linear prices), because $p'(b) = 0$. Furthermore, it always holds for our functional form of unit price $p(b_t) = \tilde{p}b_t^{\theta-1}$, for any $\tilde{p} > 0$ and θ , since $\theta > 0$.

4 Dynamics of food waste

To characterize our results analytically, we shall restrict to specific functional forms that describe preferences, storage, transformation and final assembly technologies, verifying the assumptions of our framework. We consider an additive separable logarithmic utility function $U(c_t, s_{t+1}) = \ln c_t + \mu \ln s_{t+1}$, where μ is a positive parameter that measures the relative weight of utility provided by processed ingredients. This parameter represents the intensity of the households' bias towards (ultra-)processed foods. High values of μ can describe, for instance, a strong palatability chosen by the food industry to attract consumers. Indeed, $\mu = 0$ stands for the situation without behavioural bias as stated in Corollary 1. Because we focus on the implications of this bias as a cause of food waste, our stylized framework does not specify the mechanisms that trigger such taste.

Since our primary concern is intentional food waste, we simply assume that the storage technology is linear in the quantity stored $x_t \geq 0$: $\varphi(x_t) = \varphi x_t$, with a constant $\varphi \in (0, 1)$. As for the transformation technology, we specify $h(v_t, z_t) = v_t + \phi z_t - z_t^2$, where $\phi > 0$. Following the hypotheses regarding h we made after its introduction in (2), we assume that it is a separable additive function on v_t and z_t where no ingredient is essential. It increases with v_t , reflecting the positive nutritional contribution of fresh foods. However, the term $\phi z_t - z_t^2$ increases for values of z_t between $[0, \frac{\phi}{2}]$, while it decreases for larger values. Consistent with the medical literature, crossing a threshold level of (ultra-)processed food consumption (here $\phi/2$) is harmful and the nutritional contribution of the preparation decreases with the

quantity consumed. In fact, the parameter ϕ represents the quality of (ultra-)processed foods, allowing for higher levels of consumption with nutritional benefits. About the final assembly technology g , we assume a Cobb-Douglas function $g(u_t, m_t) = u_t^\gamma m_t^{1-\gamma}$, with $\gamma \in (0, 1)$, which introduces a certain degree of complementarity between home-grown ingredients and purchased foods in the final composite meal.

With this configuration in hand, the restrictions (8)-(11) and the optimality conditions (12)-(15) lead to a two-dimensional system of difference equations that describes the dynamics of our economy with intentional food waste:

Proposition 3. *The dynamics of an equilibrium with intentional food waste reduce to the following set of difference equations for (k_t, b_t) at every $t \geq 0$:*

$$k_{t+1} = f(k_t) - p(b_t)b_t - \frac{\gamma}{1 - \gamma + \mu} \left(b_t + \frac{\phi^2}{4} \right) [p'(b_t)b_t + p(b_t)], \quad (16)$$

$$\beta f'(k_{t+1}) = \frac{p'(b_{t+1})b_{t+1} + p(b_{t+1}) \left(b_{t+1} + \frac{\phi^2}{4} \right)}{p'(b_t)b_t + p(b_t) \left(b_t + \frac{\phi^2}{4} \right)}. \quad (17)$$

Proof. See Appendix C. □

Provided the solution to this system, we can fully characterize our different sources of food waste. Considering the linear storage technology above, mechanical waste in (4) becomes $w_t^m = (1 - \varphi)(b_t - v_t)$. For $t \geq 0$, if households do not purchase any food ($b_t = 0$), there would be no mechanical waste because they did not buy fresh food either ($v_t = 0$). Otherwise, taking the optimal value of v_t in (42) from Appendix C in the formula for w_t^m , there is mechanical waste:

$$w_t^m = \frac{(1 - \varphi)\mu}{1 - \gamma + \mu} \left(b_t + \frac{\phi^2}{4} \right). \quad (18)$$

Equation 5 defines intentional waste. Since we assume that the economy starts at $t = 0$, and that the initial stock of stored food s_0 is given, if there is intentional waste, $w_0^i = s_0 - \frac{\phi}{2}$. For $t > 0$, the size of this type of food waste is computed again using the optimal value of

v_t in (42), substituting it this time in $w_{t+1}^i = \varphi(b_t - v_t) - \frac{\phi}{2}$:

$$w_{t+1}^i = \frac{\mu\varphi}{1-\gamma+\mu}b_t + \frac{\phi^2}{4} \left(\frac{\mu\varphi}{1-\gamma+\mu} - \frac{\phi}{2} \right). \quad (19)$$

It is easy to see that, as long as households purchase some food ($b_t > 0$), a sufficient condition for intentional waste (i.e., for $w_{t+1}^i > 0$) is that the quality of processed foods is high enough: $\phi > \tilde{\phi}$ where $\tilde{\phi} \equiv 2(1-\gamma+\mu)/\mu\varphi$. One should notice that this threshold decreases with μ , which represents the intensity of households' bias towards (ultra-)processed foods. Therefore, a reinforced bias due to, for example, greater palatability of processed foods, would support intentional food waste.

5 Persistent food waste

The literature on food waste often emphasizes that food waste is not just a transitory phenomenon. As noted in the introduction of the paper, levels of food waste are significant in both developing and developed countries. Furthermore, the environmental impact of food waste, as well as its implications for food security, makes this issue central concerning sustainability. The UN (see, for example, UN, 2015 and 2021) in particular includes reducing food waste as part of the Sustainable Development Goals (SDG 12.3). Other studies, such as that of Dahiya et al. (2018), de Bruin et al. (2019) or Box (2022), point out explicitly the persistent nature of food waste.

Following this perspective, we concentrate on the steady-state equilibria of the dynamical system (16) and (17), and on the corresponding stability properties. In order to study the implications of the behavioural bias, let us first consider the case of linear prices where $p(b_t) = \tilde{p} > 0$. We define steady-state equilibrium as a situation where $k_t = k_{t+1} = k^*$ and $b_t = b_{t+1} = b^*$. Taking the system at the steady-state, together with linear prices, we can compute (k^*, b^*) , where Assumption 2 ensures its uniqueness:

Proposition 4. *Our economy has a unique steady-state equilibrium (k^*, b^*) given by*

$$\beta f'(k^*) = 1, \quad (20)$$

$$b^* = \frac{1}{1 + \mu \tilde{p}} \left\{ (1 - \gamma + \mu)[f(k^*) - k^*] - \gamma \frac{\phi^2}{4} \tilde{p} \right\}. \quad (21)$$

If we consider realistic situations where $k^* > 0$, then the disposable income at the steady-state $y_d^* \equiv f(k^*) - k^*$ is strictly positive because $\beta \in (0, 1)$ in (20). As expected, from (21), a sufficiently large disposable income would allow households to purchase food: $b^* > 0$ iff $y_d^* > \tilde{y}_d \equiv \frac{\gamma \tilde{p}}{1 - \gamma + \mu} \frac{\phi^2}{4}$.

Let us assume the usual neoclassical production function $f(k_t) = Ak_t^\alpha$ with $A > 0$ and $\alpha \in (0, 1)$, where the representative household supplies inelastically one unit of labour per time unit. Then, we can set the stability properties of the steady-state:

Proposition 5. *The steady-state $(k^*, b^*) > 0$ is saddle-path stable.*

Proof. See Appendix D. □

Considering (18) and (19), the proposition confirms that our model adequately describes the dynamics of an economy where persistent food waste can arise. The economy approaches to the single steady-state $(k^*, b^*) > 0$, which represents the long-run equilibrium. Furthermore, it converges (asymptotically) following a unique trajectory that is unambiguously identified along with b_0 . Using (21) in these two expressions at the steady-state allows us to study the different sources of persistent food waste:

Proposition 6. *Suppose households are rich enough to purchase food. Then, a strong palatability of processed foods (μ) induces persistent food waste, in particular, intentional.*

Proof. See Appendix E. □

In line with Corollary 1, this outcome points to the relationship between consumer behavioural biases and food waste. If households can afford to buy part of their food, food

industry strategies can induce food waste: systematically nurturing consumers' biases towards (ultra-)processed foods, such as intensifying their palatability, leads to persistent food waste. Furthermore, this waste is not purely mechanical. Part of the food waste (namely, intentional) results from a rational household choice, which is influenced by this bias.

Considering the effect on different types of ingredients provides a deeper understanding of the channels at play. In this respect, Proposition 4 above specifies the steady-state values $(k^*, b^*) > 0$. Then, taking (42) from Appendix C at the steady-state gives the long-term quantity of fresh food:

$$v^* = \frac{1 - \gamma}{1 - \gamma + \mu} \left(b^* - \frac{\mu}{1 - \gamma} \frac{\phi^2}{4} \right). \quad (22)$$

For linear storage technology, (1) at the steady-state becomes $s^* = \varphi(b^* - v^*)$. Therefore, using (22), the amount of stored food at the steady-state is

$$s^* = \frac{\varphi\mu}{1 - \gamma + \mu} \left(b^* + \frac{\phi^2}{4} \right) > 0. \quad (23)$$

Considering linear prices, (43) in Appendix C at the steady-state determines food from home-grown production:

$$u^* = \frac{\gamma\tilde{p}}{1 - \gamma + \mu} \left(b^* + \frac{\phi^2}{4} \right) > 0. \quad (24)$$

Since we want to study the effect on each ingredient, let us concentrate on strictly positive quantities. As for $b^* > 0$, a large enough disposable income also ensures that households buy fresh food: $v^* > 0$ if and only if $y_d^* > \tilde{y}_d \equiv \tilde{y}_d + \frac{1+\mu}{1-\gamma+\mu} \frac{\mu\tilde{p}}{1-\gamma} \frac{\phi^2}{4}$.

Proposition 7. *A greater preference for ultra-processed foods increases purchased foods. The rising amount of ultra-processed foods displaces fresh and home-grown ingredients. This induces more food waste, where both mechanical and intentional waste are intensified.*

Proof. See Appendix F. □

This result extends what was observed in Proposition 6. Manipulating consumers' biases encourages food purchasing and waste. Households buy more ultra-processed foods, reducing

the quantity of fresh ingredients in their basket. In addition, ultra-processed foods will also displace home-grown production.

As noted before, food waste should not be expected to disappear as the economy develops. The next proposition states that a richer economy wastes more food:

Proposition 8. *In an economy with greater disposable income, households purchase more food, including fresh and ultra-processed ingredients. They also produce more home-grown food, but food waste still increases.*

Proof. See Appendix G. □

In a similar vein, lower prices make purchased food more affordable, but food waste increases. Moreover, cheaper foods displace home-grown production due to their substitutability in the composition of the final meal:

Proposition 9. *Cheaper food causes households to buy more food, both fresh and ultra-processed, resulting in more food waste and displacing home-grown ingredients.*

Proof. See Appendix H. □

This proposition also underlines the consequences of aggressive pricing policies. A reduction of \tilde{p} may represent another strategy often used by the processed and ultra-processed food industry to attract consumers: a central feature of the production of these types of foods is its economies of scale, which allows producers to offer them at a relative low price (among others, Martínez-Steele et al., 2017; Hall et al., 2019; and Blanco-Rojo et al., 2019). As stated by the proposition, this strategy leads households to buy more food, but also to generate more food waste. Still, considering linear prices in our stylized framework makes this strategy fully exogenous. In the next section we endogenize this channel by studying aggressive pricing policies that take the form of quantity discounts.

6 Aggressive pricing policies: quantity discounts

Let us consider $\theta \in (0, 1)$ in $p(b_t) = \tilde{p}b_t^{\theta-1}$. Unlike Section 5, where we assumed $\theta = 1$, the unit price $p(b_t)$ now decreases with the purchased quantity of food, typically representing quantity discount policies. Taking the dynamical system of Proposition 3 at the steady-state, we characterize the long-run behaviour of the economy. As before, there exists a unique steady-state value k^* , which verifies $\beta f'(k^*) = 1$. However, assuming non-linear prices in (16) leads now to a steady-state value for b^* such that

$$y_d^* = R(b^*) \equiv (1 + \chi)\tilde{p}b^{*\theta} + \chi\frac{\phi^2}{4}\tilde{p}b^{*\theta-1}, \quad (25)$$

with $\chi \equiv \frac{\gamma\theta}{1-\gamma+\mu}$. Studying the shape of function $R(b^*)$, (25) shows that quantity discounts introduce richer dynamics for the economy:

Proposition 10. *Under quantity discount policies, our economy can have multiple steady-state equilibria.*

Proof. See Appendix I. □

In contrast to linear prices, quantity discounts allow for an additional (steady-state) equilibrium: households take advantage of a reduced unit price that leads to higher levels of purchased food. However, to benefit from this opportunity, households must be wealthy enough to buy large quantities of food and then enjoy a relatively low unit price. The difference between the two equilibria reduces as disposable income decreases. There exists in fact a limit income (y_d^c) where the steady-state becomes unique (see the proof of the proposition for all details). This limit is reduced with the palatability of ultra-processed foods μ (households gain utility from the taste bias). Moreover, as we will show in the following proposition, the single steady-state is a source (i.e., unstable) as opposed to the case of multiple equilibria:

Proposition 11. *Let us consider a neoclassical production function. Assume that the disposable income is large enough, i.e. $y_d^* > y_d^c$, so that there exist two steady-states (k^*, \underline{b}) and (k^*, \bar{b}) , where $\underline{b} < \bar{b}$. The first steady-state is saddle-path stable, while the second can be either saddle-path stable or a source. If $y_d^* = y_d^c$, the unique steady-state (k^*, b^c) , with $b^c \in (\underline{b}, \bar{b})$, is a source. If $y_d^* < y_d^c$, there is no steady-state.*

Proof. See Appendix J. □

As for linear prices, the proposition states that our model, with quantity discounts, can also lead to persistent food waste. But this pricing strategy also incorporates the possibility of a second long-term equilibrium, in which households buy relatively more food, taking advantage of the discounts. Note that higher disposable incomes supports this possibility: as observed above, this would allow households to buy more food, making this new equilibrium saddle-path stable and not a source (see last condition of the proof). Furthermore, the convergence to a situation where purchased food may be relatively high also suggests the existence of a food waste channel linked to pricing strategies. We explore this possibility below.

Equations (18) and (19) describe the two different sources of food waste based on the amount of food purchased. Although price non-linearity does not allow us to provide closed-form solutions for b^* , we can still use the properties identified in Propositions 10 and 11 to characterize food waste under quantity discounts. Specifically, as stated by those two equations, mechanical and intentional food waste are linear increasing functions of b_t . If with linear prices the quantity of food purchased b_l was less than with non-linear prices, we would conclude that quantity discounts foster persistent food waste:

Proposition 12. *Consider an economy where households purchase food, including fresh and (ultra-)processed. Under enough palatability of (ultra-)processed foods (i.e., $\mu > \frac{(1-\theta)(1-\gamma)}{\theta}$), aggressive pricing strategies, such as quantity discounts, can encourage more persistent food waste. In particular, if linear prices are not too low, quantity discounts lead to more food*

purchases $\bar{b} > b_l$, which increases food waste.

Proof. See Appendix K. □

Due to non-linear prices, the analytical results in Proposition 12 are restricted to sufficient conditions. Solving (25) would provide further numerical insights. Nevertheless, sufficient conditions already underline the relationship between three key elements at play, namely palatability (μ), the strength of the quantity discount, which is directly related to the parameter θ ,⁴ and the level of linear prices (\tilde{p}). Rearranging the condition on palatability in the proposition, $\theta > \tilde{\theta} \equiv (1 - \gamma)/(1 - \gamma + \mu) \in (0, 1)$. Therefore, since μ reduces $\tilde{\theta}$, palatability increases the range of discounts ($\tilde{\theta}, 1$) that can lead to higher persistent food waste. Finally, if linear prices \tilde{p} were too low, households would not benefit much from quantity discounts: they should purchase very large amounts of food, but this option is constrained by their budget. And, therefore, the long-run amount of purchased food would be lower than with linear prices (see Figure 2 of the proof).

7 Concluding Remarks

This work presents a new channel for food waste based on consumer behavioural biases. The literature shows that the food industry often exploits biases towards (ultra-)processed foods to increase sales. We demonstrate that systematically nurturing these biases also leads to persistent food waste, including a component that is rationally decided by the households. This channel intensifies in richer economies, which is consistent with the fact that food waste does not disappear with economic development. Since cheaper foods tend to exacerbate the problem, we also investigated the contribution of aggressive pricing policies. We found in this respect that quantity discounts further encourage food waste.

The paper has several limitations due to the simplified nature of the model. To provide an analytical description of the main elements at play, we did not specify a number of economic

⁴The semi-elasticity of prices with respect to the quantity discount is $\frac{1-\theta}{b}$, so the smaller θ the greater the discount.

mechanisms. We concentrated on the implications of the causal effect of consumer biases on food waste. However, considering habit-formation, reference-point models or visceral influences (see, for instance, Loewenstein, 1996; or Frederick et al., 2002) would broaden our focus by exposing the formation of consumer biases related to (ultra-)processed foods. Food companies also decide on strategies such as the level of palatability of this type of food, taking into account technological constraints and the way consumer biases are shaped.

Extensions aimed at endogenizing these biases would provide additional justification for the so-called fat (sin) taxes. A fat tax is a surcharge often placed on (ultra-)processed foods with the goal of discouraging unhealthy diets (Vartanian et al., 2007; Allais et al., 2010; or Goulão and Pérez-Barahona, 2014). Considering our channel, fat taxes can also be supported on the grounds of internalizing the externalities behind food waste. Finally, our framework is flexible enough to reproduce a variety of dynamics. Eigenvalues cannot be complex or negative.⁵ Nevertheless, adding quantity discounts yields multiple long-run equilibria. While one steady-state is always saddle-path stable, the other may be a source. This opens the possibility of cycles that could explain fluctuations, i.e., non-monotonic trends, in food waste. The interaction between economic cycles and food market fluctuations has been widely identified in the literature. The so-called “Pork Cycle” is an example of this (Coase and Fowler, 1935; Ezekiel, 1938; Holt and Craig, 2006, Holst and Cramon-Taubadel, 2011). In particular, there is also evidence of the link between business cycles and the consumption of ultra-processed foods (for instance, Dave and Kelly, 2012; and FED, 2024). Studying cycles in our framework would provide insight into the role that consumer behavioral biases and pricing strategies play in this regard, and into the subsequent implications for fluctuations in food waste.

⁵We showed in appendices D and J that our eigenvalues cannot be complex. Furthermore, for linear and non-linear prices, the determinant of the corresponding Jacobian is strictly positive, implying that both eigenvalues have the same sign. Then, considering our different steady-states, it can be verified that these eigenvalues cannot be negative either.

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A Proof of Proposition 2

To characterize the solution to the optimization problem (\mathcal{P}), we set up the Lagrangian function:

$$\begin{aligned} \mathcal{L}(\mathbf{c}, \mathbf{s}, \mathbf{k}, \mathbf{u}, \mathbf{v}, \mathbf{b}, \mathbf{z}, \lambda_i) \equiv & \sum_{t=0}^{\infty} \beta^t \left\{ U(c_t, s_{t+1}) - \lambda_{1t} [k_{t+1} + p(b_t)b_t + u_t - f(k_t)] \right. \\ & \left. - \lambda_{2t} [c_t - g(u_t, h(v_t, z_t))] - \lambda_{3t} [s_{t+1} - \varphi(b_t - v_t)] - \lambda_{4t} (z_t - s_t) \right\}, \end{aligned}$$

where $\lambda_i \in \mathbb{R}_+$ are the associated shadow prices, with the complementary slackness conditions:

$$\lambda_{1t} [k_{t+1} + p(b_t)b_t + u_t - f(k_t)] = 0, \quad (26)$$

$$\lambda_{2t} [c_t - g(u_t, h(v_t, z_t))] = 0, \quad (27)$$

$$\lambda_{3t} [s_{t+1} - \varphi(b_t - v_t)] = 0, \quad (28)$$

$$\lambda_{4t} (z_t - s_t) = 0. \quad (29)$$

The corresponding FOCs lead to:

$$u'_{c_t} = \lambda_{2t}, \quad (30)$$

$$u'_{s_{t+1}} + \beta \lambda_{4t} = \lambda_{3t}, \quad (31)$$

$$\beta \lambda_{1_{t+1}} f'(k_{t+1}) = \lambda_{1t}, \quad (32)$$

$$\lambda_{2t} g'_{u_t} = \lambda_{1t}, \quad (33)$$

$$\lambda_{2t} g'_{h_t} h'_{v_t} = \lambda_{3t} \varphi'(b_t - v_t), \quad (34)$$

$$\lambda_{3t} \varphi'(b_t - v_t) = \lambda_{1t} [p'(b_t)b_t + p(b_t)], \quad (35)$$

$$\lambda_{2t} g'_{h_t} h'_{z_t} = \lambda_{4t}. \quad (36)$$

and the standard transversality conditions:

$$\lim_{t \rightarrow \infty} \beta^t \lambda_{1_t} k_{t+1} = 0, \quad (37)$$

$$\lim_{t \rightarrow \infty} \beta^t \lambda_{3_t} s_{t+1} = 0, \quad (38)$$

which ensure that the present value of the stock of capital and stored food will be zero at the end of the economy.

From (30), and since $u'_{c_t} > 0$ (Assumption 1), we have that $\lambda_{2_t} > 0$. Then, (27) implies that all cooked meals will never be wasted in our model: $c_t = g(u_t, h(v_t, z_t))$. Moreover, the slackness condition (29) states that intentional food waste can arise only if $\lambda_{4_t} = 0$. Hence, since $\lambda_{2_t} > 0$, (36) leads to (15) in Proposition 2, i.e., $g'_{h_t} h'_{z_t} = 0$. In particular, if the assembly technology is strictly increasing (Assumption 5), the quantity of processed food consumed maximizes its nutrient contribution: $h'_{z_t} = 0$.

If we focus on the case where intentional food waste may be possible (i.e., $\lambda_{4_t} = 0$), we easily obtain the remaining equations of Proposition 2. Combining (30), (32) and (33), one gets the Euler Equation 12. Taking $\lambda_{4_t} = 0$ in (31), $u'_{s_{t+1}} = \lambda_{3_t}$. Then, (34) leads to (13) considering (30). Combining (30)-(32), we obtain (14) from (35). Finally, we get the transversality conditions of the proposition by considering (30) and (33) in (37), and (31) in (38) with $\lambda_{4_t} = 0$.

B Proof of Corolary 1

Under our assumptions, (34) implies that $\lambda_{3_t} > 0$. In particular, in the case of no taste for processed food (i.e., $u'_{s_{t+1}} = 0$), $\beta \lambda_{4_t} = \lambda_{3_t}$ from (31). Since $\beta > 0$ and $\lambda_{3_t} > 0$, it is true that $\lambda_{4_t} > 0$. Therefore, from (29), there would be no intentional food waste as stated in the corolary.

C Proof of Proposition 3.

Let us consider the functional forms in Section 4. Taking (11) in (15) gives

$$m_t = v_t + \frac{\phi^2}{4}. \quad (39)$$

Applying (39) in (9) and (13), and combining both equations, yields

$$s_{t+1} = \frac{\mu}{1-\gamma} \varphi'(b_t - v_t) \left(v_t + \frac{\phi^2}{4} \right). \quad (40)$$

Considering (9) in (14), together with (40), results in

$$u_t = \frac{\gamma}{1-\gamma} [p'(b_t)b_t + p(b_t)] \left(v_t + \frac{\phi^2}{4} \right). \quad (41)$$

With a linear storage technology, we get

$$v_t = \left(1 + \frac{\mu}{1-\gamma} \right)^{-1} \left(b_t - \frac{\mu}{1-\gamma} \frac{\phi^2}{4} \right) \quad (42)$$

by combining (8) and (40). Taking (42) into (41) leads to

$$u_t = \frac{\gamma}{1-\gamma+\mu} [p'(b_t)b_t + p(b_t)] \left(b_t + \frac{\phi^2}{4} \right). \quad (43)$$

Finally, using (43) in (10) gives us Equation 16 of the proposition.

Regarding the remaining equation of the system, we get

$$\beta f'(k_{t+1}) = \frac{u_{t+1}}{u_t} \quad (44)$$

by applying (39) in (9) and (12), and combining them. Taking (41) into (44) yields

$$\beta f'(k_{t+1}) = \frac{p'(b_{t+1})b_{t+1} + p(b_{t+1})}{p'(b_t)b_t + p(b_t)} \frac{v_{t+1} + \frac{\phi^2}{4}}{v_t + \frac{\phi^2}{4}}. \quad (45)$$

Using (42) in (45) leads to (17).

D Proof of Proposition 5.

With linear prices and the Cobb-Douglas production function, the system (16) and (17) can be rewritten as

$$k_{t+1} = \eta(k_t, b_t) \equiv Ak_t^\alpha - \tilde{p}b_t - \frac{\gamma}{1-\gamma+\mu}\tilde{p}\left(b_t + \frac{\phi^2}{4}\right), \quad (46)$$

$$b_{t+1} = \xi(k_t, b_t) \equiv \alpha\beta A \left[Ak_t^\alpha - \tilde{p}b_t - \frac{\gamma}{1-\gamma+\mu}\tilde{p}\left(b_t + \frac{\phi^2}{4}\right) \right]^{\alpha-1} \left(b_t + \frac{\phi^2}{4} \right) - \frac{\phi^2}{4}. \quad (47)$$

The corresponding steady-state (k^*, b^*) is

$$k^* = (\alpha\beta A)^{\frac{1}{1-\alpha}}, \quad (48)$$

$$b^* = \frac{1}{1+\mu}\frac{1}{\tilde{p}} \left[(1-\gamma+\mu)y_d^* - \gamma\frac{\phi^2}{4}\tilde{p} \right]. \quad (49)$$

where $y_d^* \equiv Ak^{*\alpha} - k^*$ is the disposable income at the steady-state. k^* is strictly positive while, as observed about Proposition 4, $b^* > 0$ iff households have a large enough disposable income. Then, the Jacobian associated to (46) and (47) evaluated at the steady-state (48) and (49) is

$$J \equiv \begin{bmatrix} \frac{1}{\beta} & -\tilde{p}\frac{1+\mu}{1-\gamma+\mu} \\ \alpha A \left(b^* + \frac{\phi^2}{4} \right) (\alpha-1)(\alpha\beta A)^{\frac{\alpha-2}{1-\alpha}} & 1 + (\alpha\beta A)^{-\frac{1}{1-\alpha}}(1-\alpha)\tilde{p}\frac{1+\mu}{1-\gamma+\mu} \left(b^* + \frac{\phi^2}{4} \right) \end{bmatrix}. \quad (50)$$

The determinant and the trace of the Jacobian are, respectively,

$$D = \frac{1}{\beta}, \quad (51)$$

$$T = 1 + \frac{1}{\beta} + (\alpha\beta A)^{-\frac{1}{1-\alpha}}(1-\alpha)\tilde{p}\frac{1+\mu}{1-\gamma+\mu} \left(b^* + \frac{\phi^2}{4} \right). \quad (52)$$

For $b^* > 0$, $|1 + D| < |T|$. Hence, following de la Croix and Michel (2004) (page 322), the steady-state is saddle-path stable.

Note that this outcome also eliminates the possibility of complex eigenvalues, which would imply indeterminacy in our framework because b_0 is not given. If the eigenvalues were complex, one would be the complex conjugate of the other and then both would have the same modulus. This would contradict the result above.

E Proof of Proposition 6.

Replacing b^* in (19) at the steady-state by (21), and rearranging terms, we obtain

$$w^{i*} = \frac{\mu\varphi}{1+\mu} \frac{y_d^*}{\tilde{p}} - \frac{1}{1-\gamma+\mu} \left(\frac{\phi}{2}\right)^2 \left[\frac{\mu\varphi}{1+\mu} \gamma + \frac{2(1-\gamma) + \mu(2-\phi\varphi)}{\phi} \right]. \quad (53)$$

Then, $w^{i*} > 0$ iff

$$\frac{y_d^*}{\tilde{p}} > \frac{\gamma}{1-\gamma+\mu} \left(\frac{\phi}{2}\right)^2 + \frac{1}{1-\gamma+\mu} \left(\frac{\phi}{2}\right)^2 \frac{1+\mu}{\mu\varphi\phi} [2(1-\gamma) + \mu(2-\phi\varphi)]. \quad (54)$$

As observed regarding Proposition 4, let us assume that the disposable income at the steady-state is enough to allow households to purchase food (i.e., $b^* > 0$): $y_d^* > \tilde{y}_d$. Then, using the definition of \tilde{y}_d , $\frac{y_d^*}{\tilde{p}} > \frac{\gamma}{1-\gamma+\mu} \left(\frac{\phi}{2}\right)^2$. Consider that the quality of (ultra-)processed foods is high enough, as observed in (19): $\phi > \tilde{\phi}$. The definition of $\tilde{\phi}$ leads us to conclude that the term $2(1-\gamma) + \mu(2-\phi\varphi)$ in (54) is negative. Therefore, under $y_d^* > \tilde{y}_d$ the condition (54) is verified and $w^{i*} > 0$. Notice finally that a strong palatability is represented by a high value of μ . Since the threshold $\tilde{\phi}$ decreases with μ , for a given quality ϕ , we can always find a $\mu > 0$ such that $\phi > \tilde{\phi}$: $\mu > \frac{2(1-\gamma)}{\gamma\phi-2}$.

Regarding mechanical food waste, $b^* > 0$ in (18) ensures a persistent $w^{m*} > 0$. Hence, the total food waste of our economy will be $w^* = w^{i*} + w^{m*} > 0$, with both intentional ($w^{i*} > 0$) and mechanical ($w^{m*} > 0$) food waste.

F Proof of Proposition 7.

In our model, a greater preference for ultra-processed foods is represented by an increase of the parameter μ . Considering (20) and (21),

$$\frac{\partial b^*}{\partial \mu} = \frac{\gamma}{\tilde{p}(1+\mu)^2} \left(y_d^* + \frac{\phi^2}{4} \tilde{p} \right) > 0. \quad (55)$$

Therefore, the amount of purchased food rises.

From (22), taking (21) and (55), yields

$$\frac{\partial v^*}{\partial \mu} = -\frac{1-\gamma}{(1+\mu)^2} \left(\frac{y_d^*}{\tilde{p}} + \frac{\phi^2}{4} \right) < 0, \quad (56)$$

implying a reduction of fresh food in the basket. Hence, the amount of ultra-processed foods, $b^* - v^*$, increases.

Combining (22) and (23),

$$\frac{\partial u^*}{\partial \mu} = \frac{\gamma \tilde{p}}{\varphi \mu} \left(\frac{\partial s^*}{\partial \mu} - \frac{s^*}{\mu} \right). \quad (57)$$

Since $s^* = \varphi(b^* - v^*)$, $\partial s^*/\partial \mu = \varphi(\partial b^*/\partial \mu - \partial v^*/\partial \mu)$. Considering (55) and (56) above,

$$\frac{\partial s^*}{\partial \mu} = \frac{\varphi}{\tilde{p}(1+\mu)^2} \left(y_d^* + \frac{\phi^2}{4} \tilde{p} \right) > 0. \quad (58)$$

Moreover, taking (21) and (23),

$$\frac{s^*}{\mu} = \frac{\varphi}{\tilde{p}(1+\mu)} \left(y_d^* + \frac{\phi^2}{4} \tilde{p} \right). \quad (59)$$

Applying (58) and (59) in (57),

$$\frac{\partial u^*}{\partial \mu} = -\frac{\gamma}{1+\mu} \left(y_d^* + \frac{\phi^2}{4} \tilde{p} \right) < 0. \quad (60)$$

Then, the quantity of home-grown ingredients is also reduced.

Regarding food waste, since $w^{m*} = (1 - \varphi)(b^* - v^*)$, mechanical food waste increases with μ because of (55) and (56) above. Intentional food waste is $w^{i*} = s^* - \frac{\phi}{2}$. Since s^* increases with μ (as stated in Equation 58), intentional waste increases too. Therefore, total food waste $w^* = w^{i*} + w^{m*}$ rises.

G Proof of Proposition 8.

From (21), since $f(k^*) - k^*$ is the disposable income y_d ,

$$\frac{\partial b^*}{\partial y_d} = \frac{1 - \gamma + \mu}{\tilde{p}(1 + \mu)} > 0. \quad (61)$$

Then, a higher disposable income raises purchased food. Considering (23), (24) and (61), one can directly see that $\partial v^*/\partial y_d$, $\partial s^*/\partial y_d$ and $\partial u^*/\partial y_d$ are strictly positive. Therefore, the quantity of all the ingredients increases. Since $w^{m*} = (1 - \varphi)s^*$ and $w^{i*} = s^* - \frac{\phi}{2}$, we finally conclude that $\partial w^{m*}/\partial y_d > 0$ and $\partial w^{i*}/\partial y_d > 0$, implying that all sources of food waste are reinforced and total food waste rises.

H Proof of Proposition 9.

From (21),

$$\frac{\partial b^*}{\partial \tilde{p}} = -\frac{1}{(1 + \mu)\tilde{p}^2} \left[(1 - \gamma + \mu)y_d - \gamma \frac{\phi^2}{4} \tilde{p} \right] - \frac{\gamma}{(1 + \mu)\tilde{p}} \frac{\phi^2}{4}, \quad (62)$$

which is strictly negative under our assumption of large enough disposable income. Considering (22) and (23), one can conclude that $\partial v^*/\partial \tilde{p}$ and $\partial s^*/\partial \tilde{p}$ are strictly negative too. Consequently, reducing \tilde{p} increases the purchase of food, in all its types (fresh and ultra-processed). Furthermore, since $w^{m*} = (1 - \varphi)s^*$ and $w^{i*} = s^* - \frac{\phi}{2}$, mechanical and intentional waste increase and, therefore, total food waste also intensifies.

Finally, from (24),

$$\frac{\partial u^*}{\partial \tilde{p}} = \frac{\gamma}{1 - \gamma + \mu} \left(\tilde{p} \frac{\partial b^*}{\partial \tilde{p}} + b^* + \frac{\phi^2}{4} \right). \quad (63)$$

Taking (21) and (62) in (63), $\frac{\partial u^*}{\partial \tilde{p}} = \frac{\gamma}{1+\mu} \frac{\phi^2}{4} > 0$. Therefore, cheaper food reduces the quantity of home-grown ingredients.

I Proof of Proposition 10

Equation 16 at the steady-state, with $p(b^*) = \tilde{p}b^{*\theta-1}$, becomes (25). From (17) at the steady-state, there exists a unique k^* verifying $\beta f'(k^*) = 1$. Then, the steady-state value b^* is obtained as the intersection of the function $R(b^*)$ and the disposable income y_d^* in Figure 1. Since k^* does not depend on b^* , y_d^* is just an horizontal line. However, the

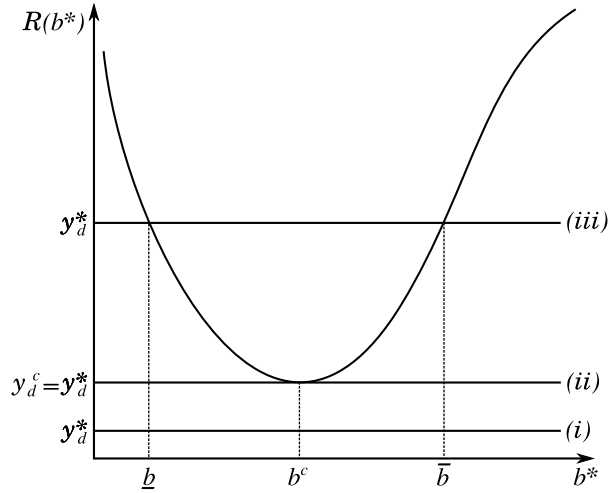


Figure 1: Multiple steady-states

function $R(b^*)$ is not linear because $\theta \in (0, 1)$. It is easy to see that $\lim_{b^* \rightarrow \infty} R(b^*) = \infty$ and $\lim_{b^* \rightarrow 0} R(b^*) = \infty$. Defining $b^c \equiv \frac{\chi}{1+\chi} \frac{1-\theta}{\theta} \frac{\phi^2}{4}$, we also find that $R'(b^*) < 0$ for $b^* < b^c$, $R'(b^*) = 0$ for $b^* = b^c$, and $R'(b^*) > 0$ for $b^* > b^c$. Moreover, identifying the inflection point $b^{cc} \equiv \frac{\chi}{1+\chi} \frac{2-\theta}{\theta} \frac{\phi^2}{4} > b^c$, we can establish that $R(b^*)$ is first convex (i.e., $R''(b^*) > 0$ for $b^* < b^{cc}$), and concave after b^{cc} (i.e., $R''(b^*) < 0$ for $b^* > b^{cc}$).

Figure 1 identifies three possibilities for b^* provided the positivity of all other variables. Let us define $y_d^c \equiv \frac{1+\chi}{1-\theta} \tilde{p} b^c{}^\theta$. If the disposable income is too low (i.e., $y_d^* < y_d^c$) there is no steady-state as illustrated by case (i) in the figure. If $y_d^* = y_d^c$, b^c is the unique steady-state as in (ii). However, if households are rich enough as in (iii) (i.e., $y_d^* > y_d^c$), there are two steady-states $b^* = \{\underline{b}, \bar{b}\}$ such that $\underline{b} < b^c < \bar{b}$.

J Proof of Proposition 11

We already showed in the proof of Proposition 10 that there is no steady-state when $y_d^* < y_d^c$. Let us then focus on situations where households are rich enough, i.e., $y_d^* \geq y_d^c$. For our non-linear prices and neoclassical production function, the dynamical system (16) and (17) becomes

$$0 = M_1(k_{t+1}, k_t, b_{t+1}, b_t) \equiv k_{t+1} - Ak_t^\alpha + \tilde{p}b_t^\theta - \frac{\gamma}{1-\gamma+\mu} \tilde{p}\theta b_t^{\theta-1} \left(b_t + \frac{\phi^2}{4} \right), \quad (64)$$

$$0 = M_2(k_{t+1}, k_t, b_{t+1}, b_t) \equiv \left(\frac{b_t}{b_{t+1}} \right)^{1-\theta} \frac{b_{t+1} + \frac{\phi^2}{4}}{b_t + \frac{\phi^2}{4}} - \alpha\beta Ak_{t+1}^\alpha. \quad (65)$$

Since $k^* = (\alpha\beta A)^{\frac{1}{1-\alpha}}$, linearising the system around a steady-state (k^*, b^*) yields the Jacobian

$$J \equiv \begin{bmatrix} \frac{1}{\beta} & \tilde{p}b^{*\theta-2} \left[\chi(1-\theta)\frac{\phi^2}{4} - (1+\chi)\theta b^* \right] \\ \frac{b^* + \frac{\phi^2}{4}}{\theta(b^* + \frac{\phi^2}{4}) - \frac{\phi^2}{4}} \frac{\alpha-1}{\beta} \frac{b^*}{k^*} & 1 + \frac{b^* + \frac{\phi^2}{4}}{\theta(b^* + \frac{\phi^2}{4}) - \frac{\phi^2}{4}} \frac{\alpha-1}{k^*} \tilde{p}b^{*\theta-1} \left[\chi(1-\theta)\frac{\phi^2}{4} - (1+\chi)\theta b^* \right] \end{bmatrix}. \quad (66)$$

The determinant and the trace of J are, respectively,

$$D = \frac{1}{\beta}, \quad (67)$$

$$T = 1 + \frac{1}{\beta} + \tau(b^*), \quad (68)$$

with

$$\tau(b^*) \equiv (1 - \alpha)(1 + \chi) \left(b^* + \frac{\phi^2}{4} \right) \frac{\tilde{p}b^{*\theta-1}}{k^*} \frac{b^* - b^c}{b^* - \frac{1+\chi}{\chi}b^c}. \quad (69)$$

Then, the eigenvalues λ_1 and λ_2 of J verify

$$(\lambda_1 - 1) \left(1 - \frac{1}{\lambda_1 \beta} \right) = \tau(b^*), \quad (70)$$

$$\lambda_2 = \frac{1}{\lambda_1 \beta}. \quad (71)$$

As with linear prices, we can show that it is impossible to have complex eigenvalues. Let us assume that λ_1 is complex. Then, λ_2 is the complex conjugate of λ_1 . Using (70) and (71), $(\lambda_1 - 1)(1 - \lambda_2) = \tau(b^*)$. Since $\tau(b^*)$ is a real number and the trace in (68) is equal to $\lambda_1 + \lambda_2$, one can check that complex eigenvalues lead to contradictions.

Considering real eigenvalues in (70) and (71), let us first study how the sign of $\tau(b^*)$ determines whether the eigenvalues are greater or lower than 1. If $\tau(b^*) = 0$, one eigenvalue is equal to 1 and the other is equal to $1/\beta$, which is greater than 1 because $\beta \in (0, 1)$. Therefore, the steady-state would be a source. If $\tau(b^*) > 0$, $(\lambda_1 - 1)(1 - \lambda_2) > 0$. Then, one eigenvalue is lower than 1 while the other is greater than 1, which proves that the steady-state would be saddle-path stable. Similarly, it can be shown that both eigenvalues are greater than 1 if $\tau(b^*) < 0$, implying that the steady-state would be a source.

When $y_d^* = y_d^c$, there is a unique steady-state value $b^* = b^c$ with $b^c \in (\underline{b}, \bar{b})$ (see proof of Proposition 10). For this case, $\tau(b^c) = 0$ and, then, the steady-state (k^*, b^c) is a source. If $y_d^* > y_d^c$ the steady-state b^* can take two values $b^* = \{\underline{b}, \bar{b}\}$ such that $\underline{b} < b^c < \bar{b}$. For $\underline{b} < b^c$ we can see that $\tau(\underline{b}) > 0$ and, therefore, (k^*, \underline{b}) is saddle-path stable. Finally, for $\bar{b} > b^c$ it is easy to verify that $\tau(\bar{b}) > 0$ if $\bar{b} > \frac{1-\theta}{\theta} \frac{\phi^2}{4}$ and, then, (k^*, \bar{b}) is saddle-path stable. Otherwise, it is a source.

K Proof of Proposition 12

The proof is organized in two steps. Step 1 identifies conditions for $\underline{b} < b^c < \bar{b}$ where first, the steady-state \underline{b} disappears because it would be associated with non-positive amounts of fresh ingredients. This arises whenever $\underline{b} < \frac{\mu}{1-\gamma} \frac{\phi^2}{4}$ in (22). And second, \bar{b} is saddle-path stable (i.e., $\bar{b} > \frac{1-\theta}{\theta} \frac{\phi^2}{4}$). Step 2 sets conditions for $b_l < \bar{b}$, which directly implies more persistent food waste.

Step 1: let us assume a high enough disposable income y_d^* such that $\underline{b} < b^c < \bar{b}$ (see proof of Proposition 10). Since $\frac{\phi^2}{4} > 0$, the palatability condition of the proposition implies that $\frac{1-\theta}{\theta} \frac{\phi^2}{4} < \frac{\mu}{1-\gamma} \frac{\phi^2}{4}$. From the proof of Proposition 10, $b^c \equiv \frac{\chi}{1+\chi} \frac{1-\theta}{\theta} \frac{\phi^2}{4} < \frac{1-\theta}{\theta} \frac{\phi^2}{4}$ because $\chi > 0$. Therefore $\underline{b} < \frac{\mu}{1-\gamma} \frac{\phi^2}{4}$ and, hence, \underline{b} cannot be a steady-state because $v^* < 0$. However, if \bar{b} is a steady-state compatible with $v^* > 0$, $\bar{b} > \frac{\mu}{1-\gamma} \frac{\phi^2}{4}$. This implies that $\bar{b} > \frac{1-\theta}{\theta} \frac{\phi^2}{4}$ and, then, \bar{b} is saddle-path stable.

Step 2: in general, there is no explicit solution for \bar{b} . Nevertheless, we can still characterize the solution by analyzing $R(b^*)$. Function $R(b^*)$ for quantity discounts is $R_{nl}(b^*) \equiv R(b^*)$ in (25), while for linear prices it is given by $R_l(b^*) \equiv (1 + \chi_l)\tilde{p}b^* + \chi_l \frac{\phi^2}{4}\tilde{p}$ with $\chi_l = \chi/\theta$. $R_{nl}(b^*)$ as was described in the proof of Proposition 10. $R_l(b^*)$ is a straight line with intercept $R_l(0) = \tilde{y}_d$ and slope $R'_l(b^*) = (1 + \chi_l)\tilde{p}$. Figure 2 illustrates both functions, where $\tilde{y}_d > y_d^c$ without loss of generality. One can directly see that $b_l < \bar{b}$ iff $R_l(b^*)$ is steeper than the dashed line connecting the intercept \tilde{y}_d and the point (\bar{b}, y_d^*) , i.e.,

$$(1 + \chi_l)\tilde{p} > \frac{y_d^* - \tilde{y}_d}{\bar{b}}, \quad (72)$$

which states that linear prices \tilde{p} should not be too low. Without an explicit solution for \bar{b} , we can still set a sufficient condition because $b^c < \bar{b}$, where b^c was defined in the proof of Proposition 10: if $\tilde{p} > \frac{1}{1+\chi_l} \frac{y_d^* - \tilde{y}_d}{b^c}$, $b_l < \bar{b}$. Considering the definitions of b^c and \tilde{y}_d , and

rearranging terms, this condition becomes:

$$\tilde{p} > \Theta \left(\frac{2\theta}{\phi} \right)^2 y_d^*, \quad (73)$$

where $\Theta \equiv [(1 - \theta)(\theta + \chi) + \theta(1 + \chi)]^{-1}$ is a positive constant.

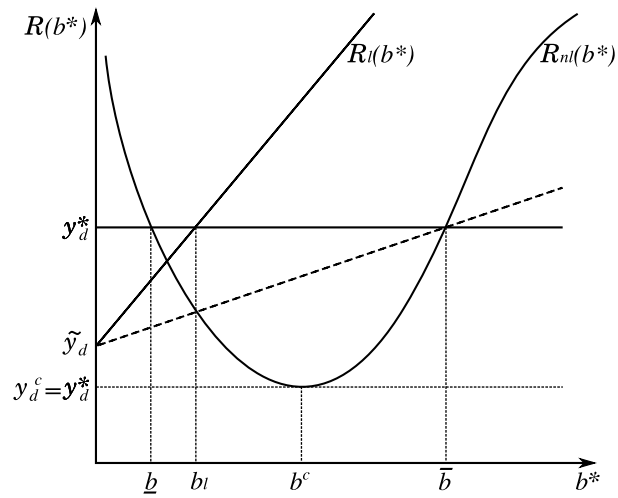


Figure 2: Quantity discounts and food waste